Embedded Sensors for Autonomous Air Systems

LRIR 09RW10COR

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Materials & Microsystems
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Integrity ★ Service ★ Excellence

Report Documentation Page

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Embedded Sensors for Air Vehicles

LRIR 09RW10COR – Dickinson (RW) / Baur (RX) / Reich (RQ)

Bio-like Flow Sensing

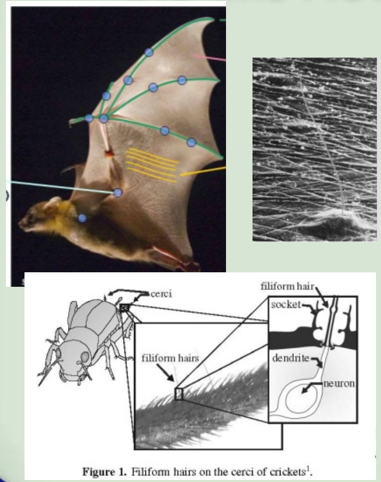
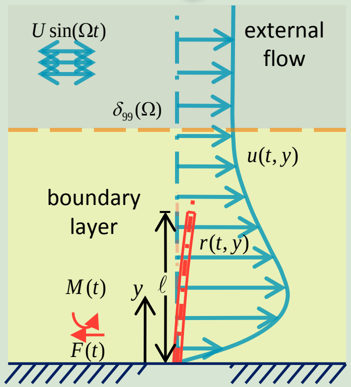


Figure 1. Filiform hairs on the cerci of crickets[1].

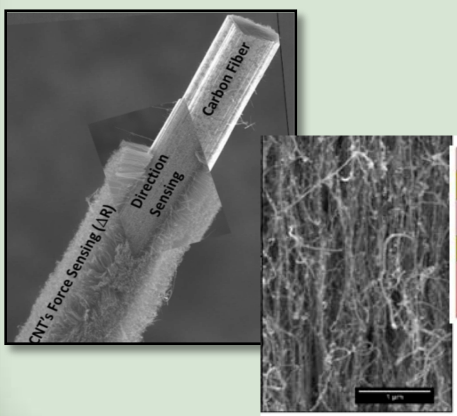


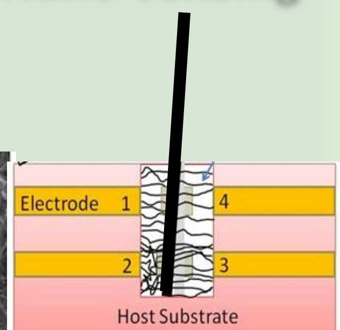
Ben Dickinson - RW

Can we enable "fly by feel" with "insect grade" hair flow sensing by understanding

Air Flow->
Hair Deflection ->
Nano-array transduction ->
Aero State Awareness

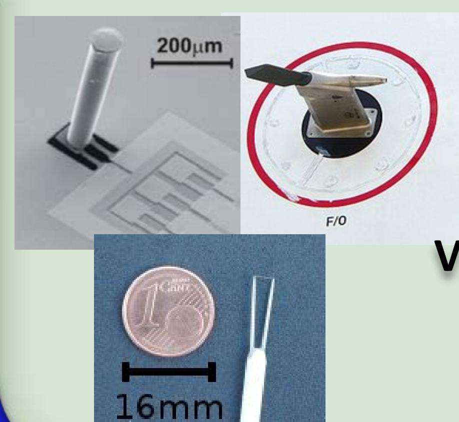
Hierarchical Fiber Nano-sensing



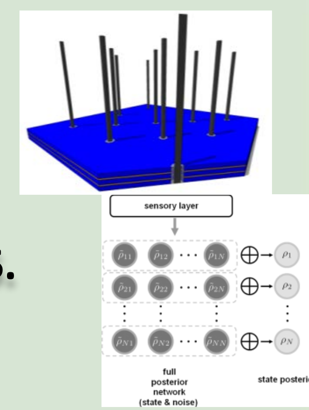


Jeff Baur - RX

"Insect Grade" Sensors to "Feel"



VS.



Greg Reich - RQ

Embedded Sensors for Air Vehicles

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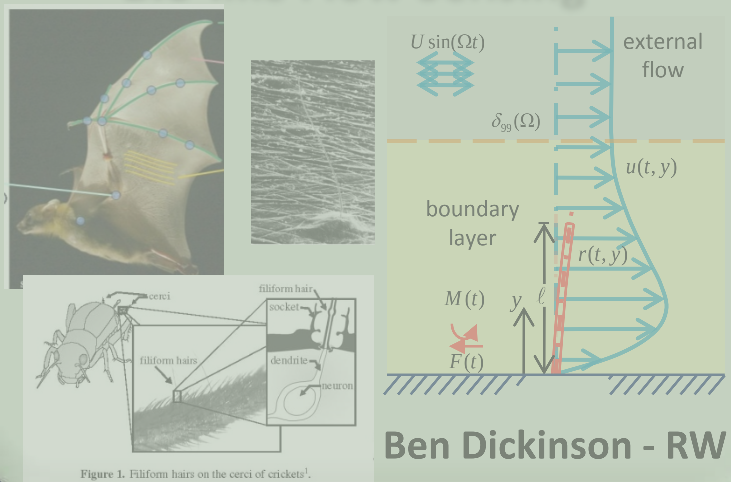
Bio-like Flow Sensing

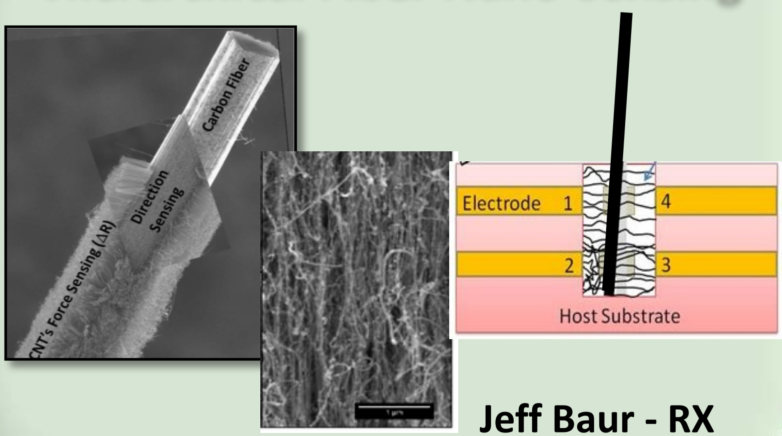


Ben Dickinson - RW

1. Origin/sensitivity of CNT arrays to force transduction?
2. Compression mechanics of CNT Arrays?
3. Best methods for quantifying CNT arrays mechanics?
4. Proof-of-concept as a artificial hair flow sensor?

?

Hierarchical Fiber Nano-sensing



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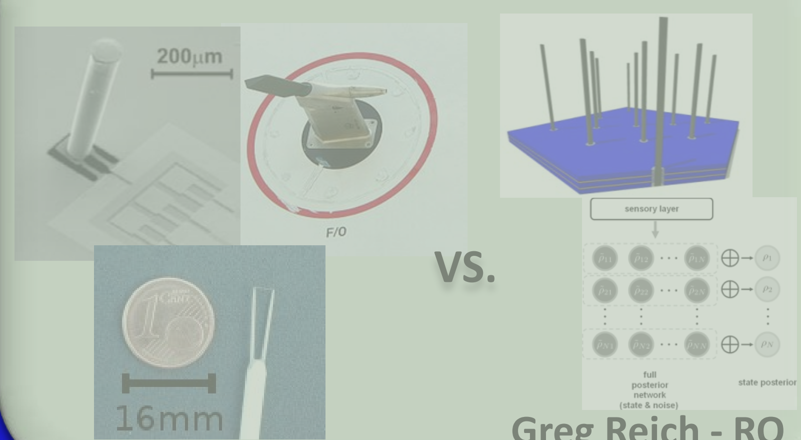
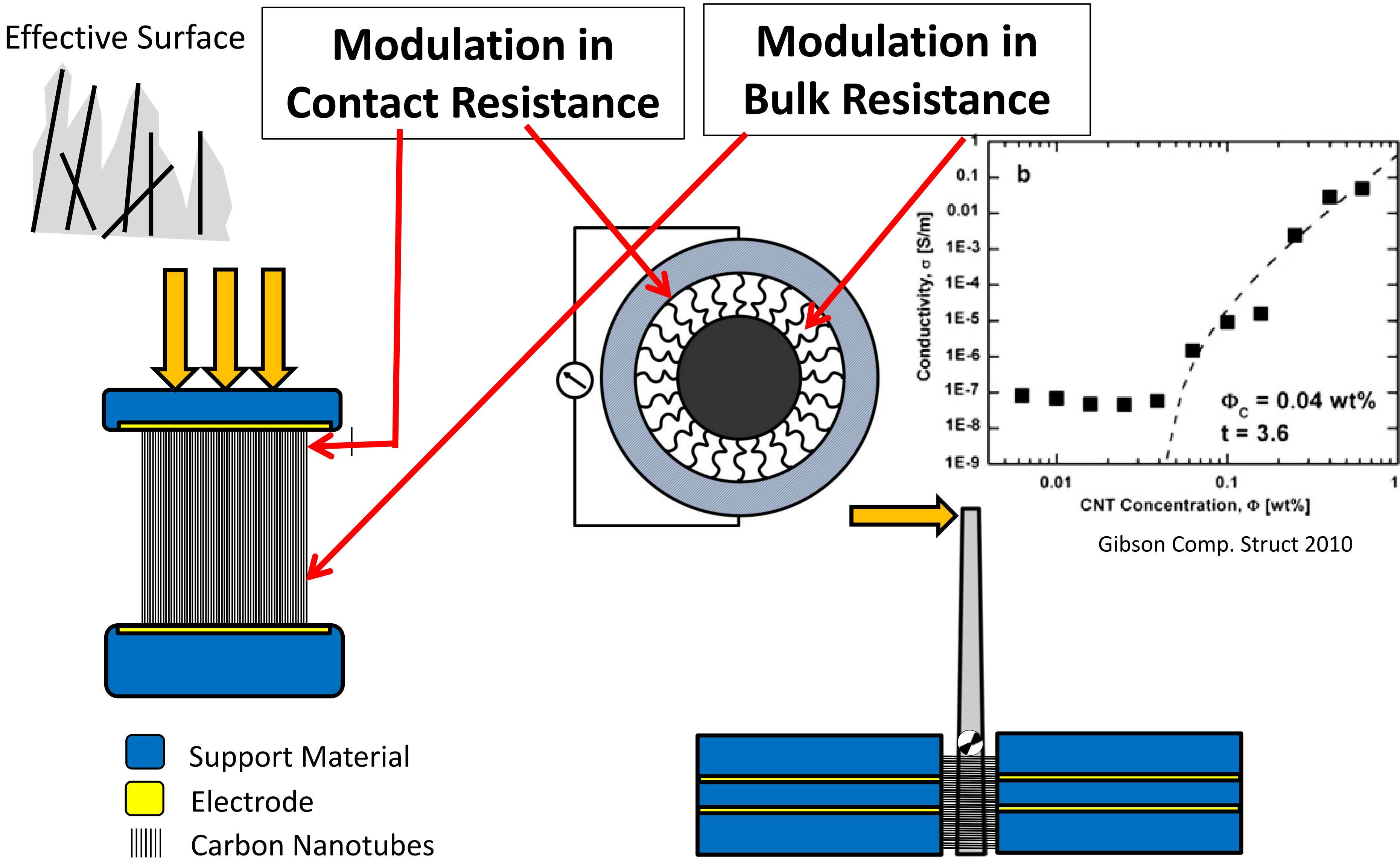
"Insect Grade" Sensors to "Feel"



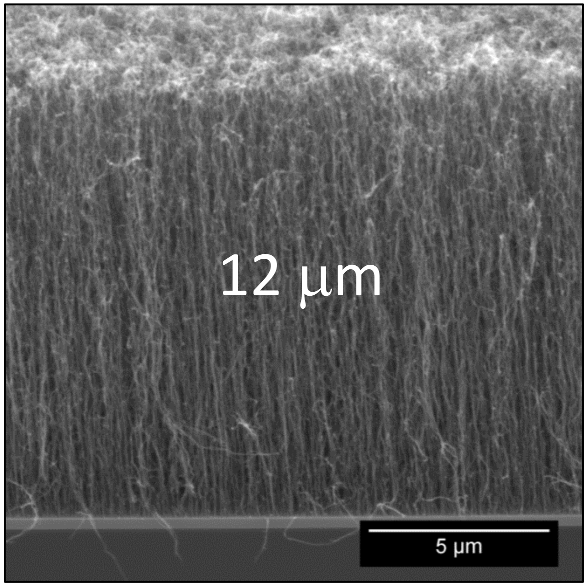
VS.

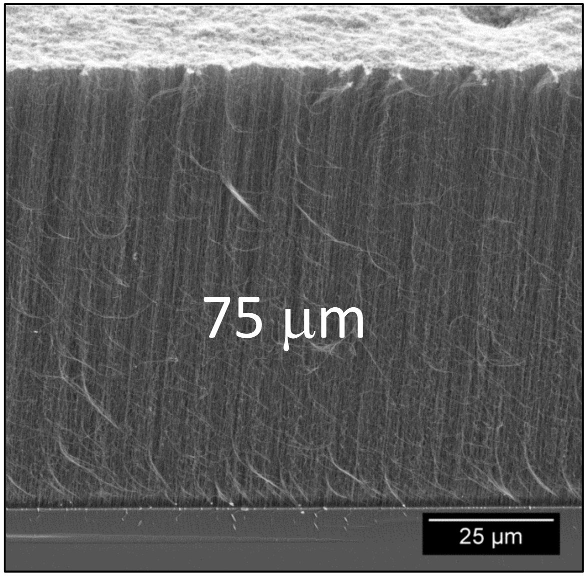
Greg Reich - RQ

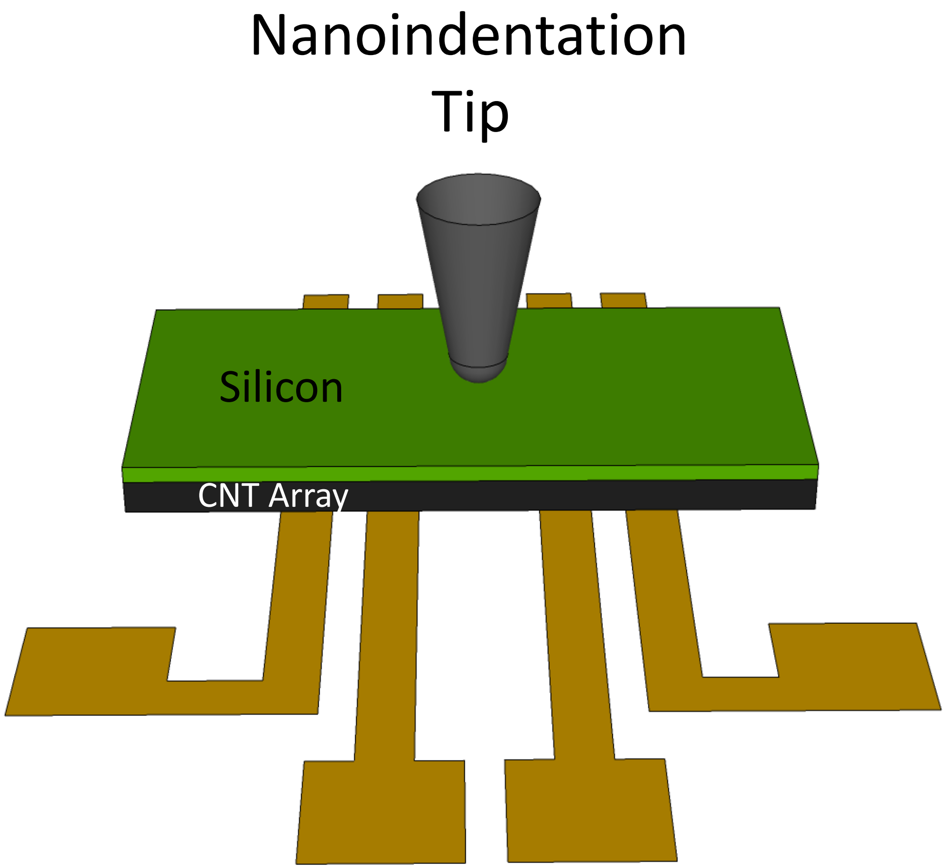
1. Origin of Mechano-Resistive Sensitivity



Planar CNT Array
4-Wire Resistance Measurements



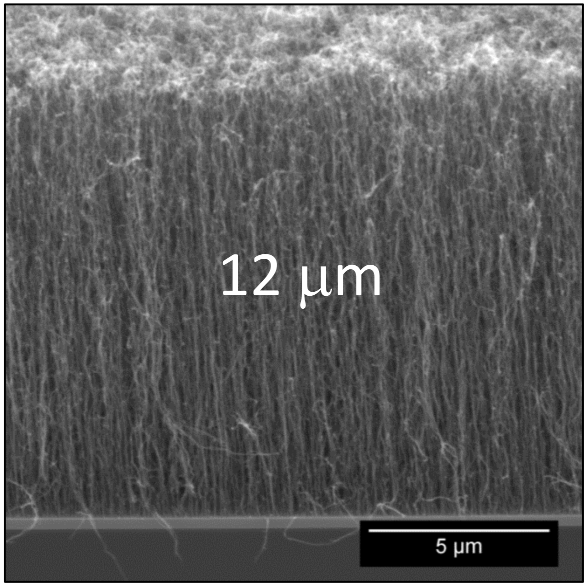


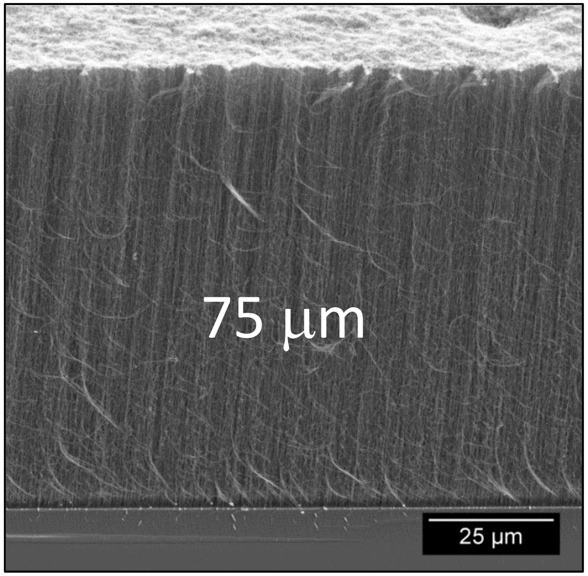


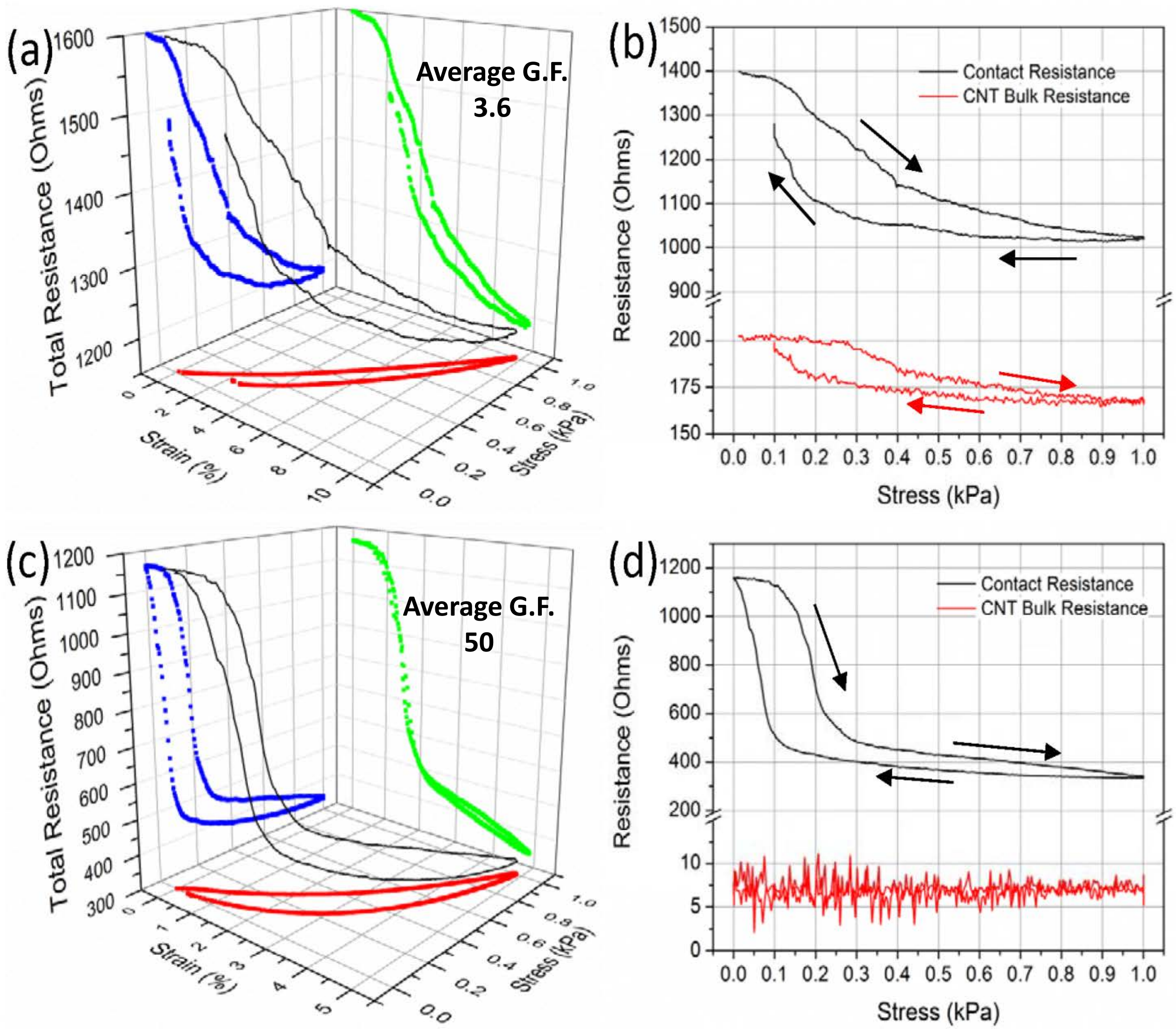
4-Wire Measurement

Planar CNT Array

4-Wire Resistance Measurements

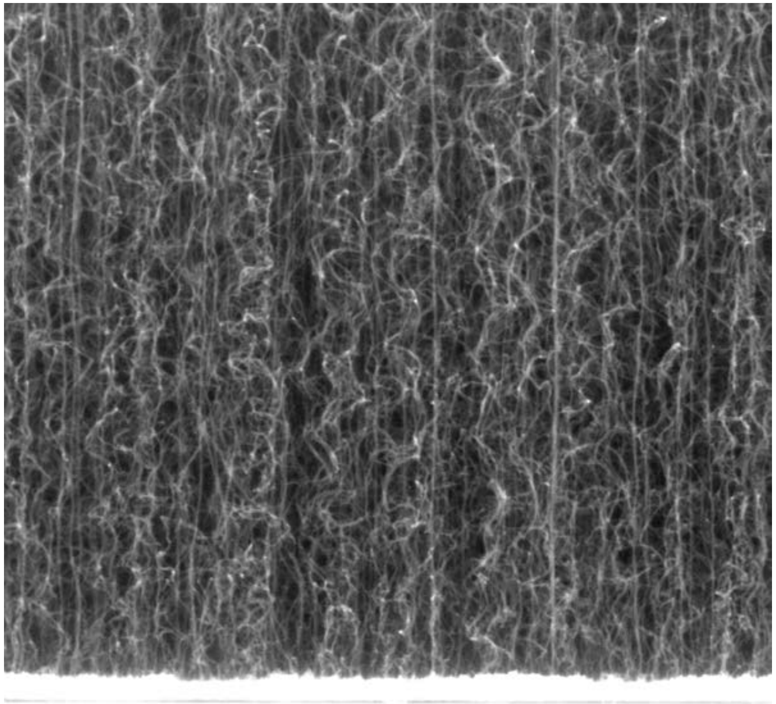




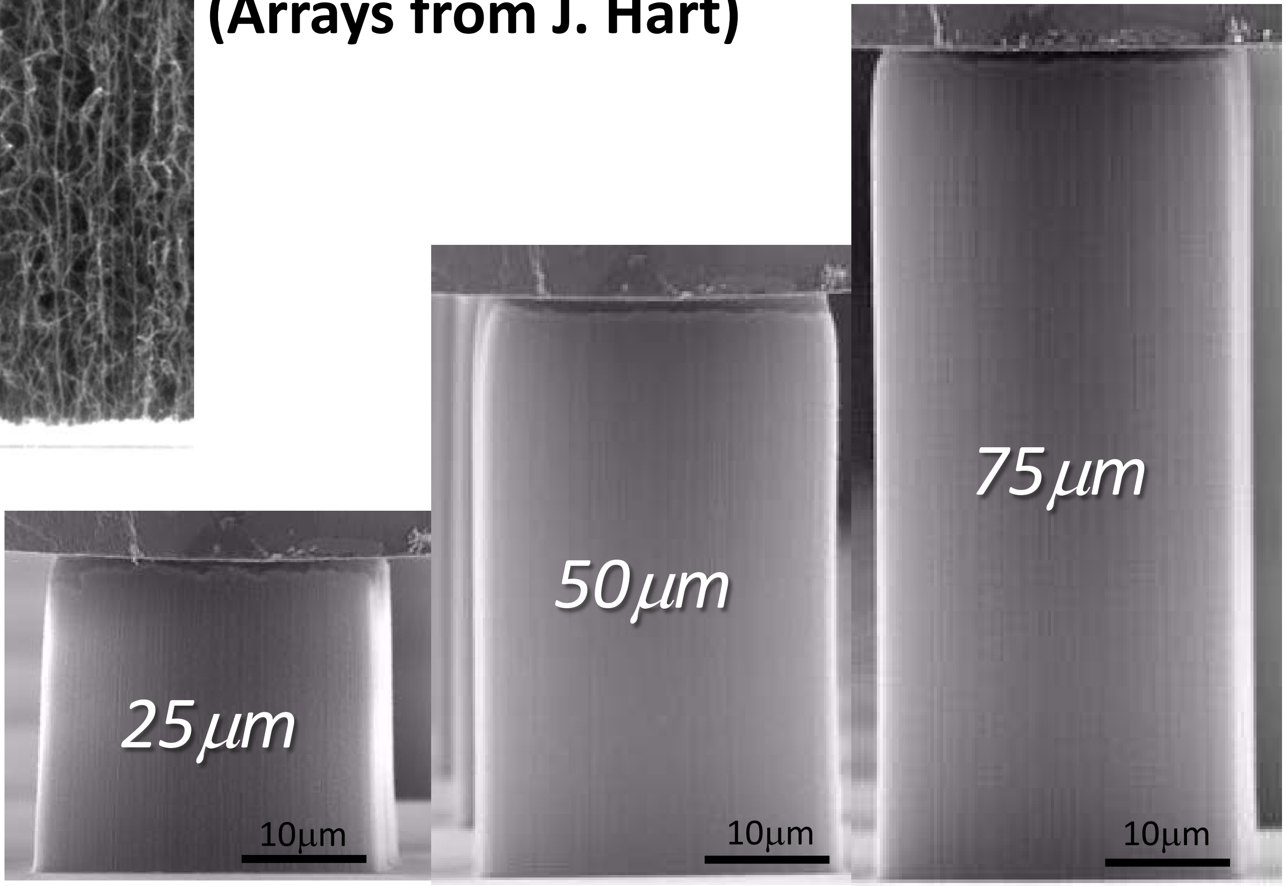


In Situ SEM Compression

CNT Array Columns



Array morphology enables traceability of individual CNT features during deformation
(Arrays from J. Hart)



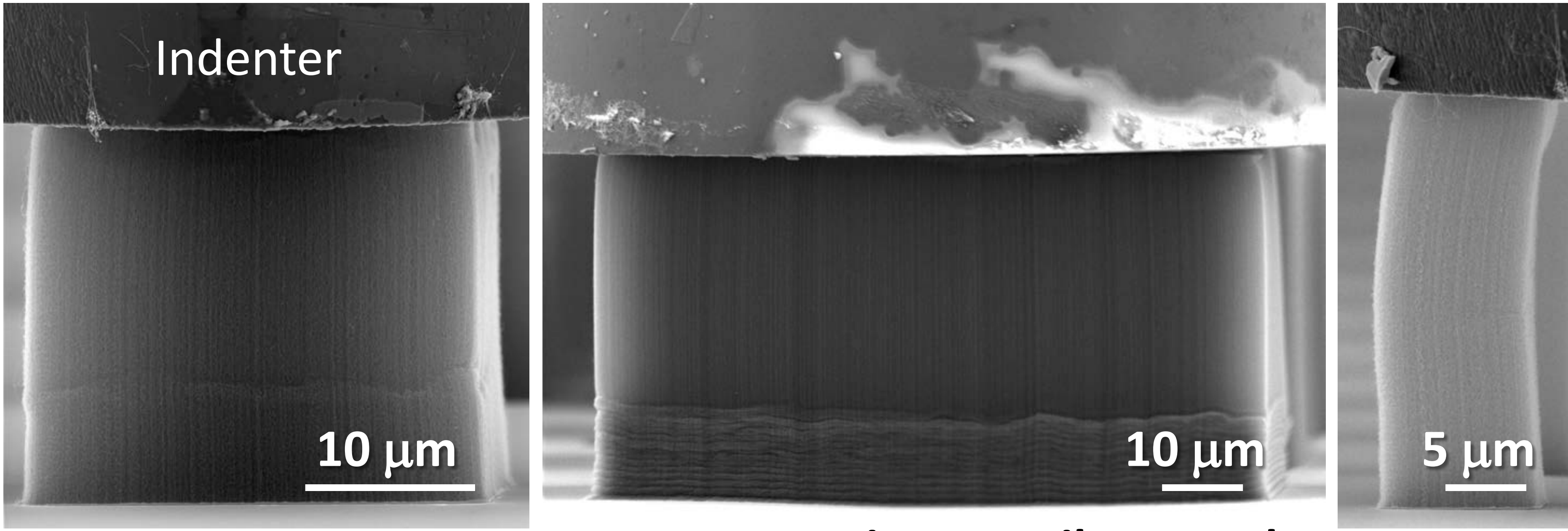
Heights:
25, 50, and 75µm

Widths:
10, 25, and 100 µm

In Situ SEM Compression

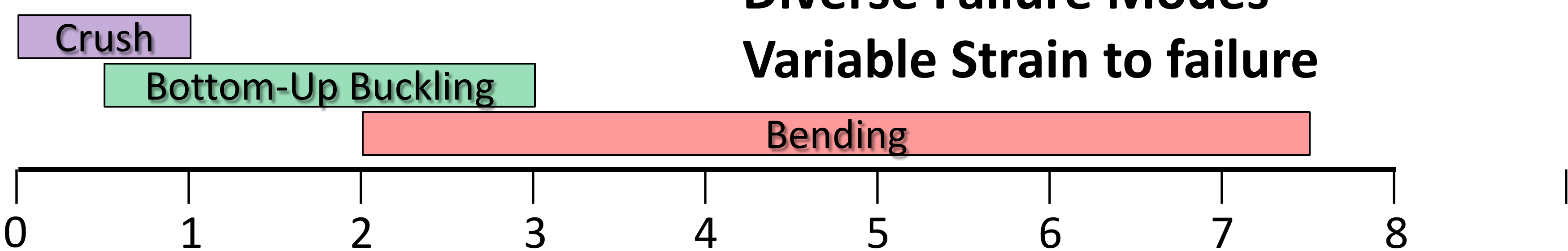
CNT Array Columns

Crushing | Bottom-Up Buckling | Bending



Diverse Failure Modes

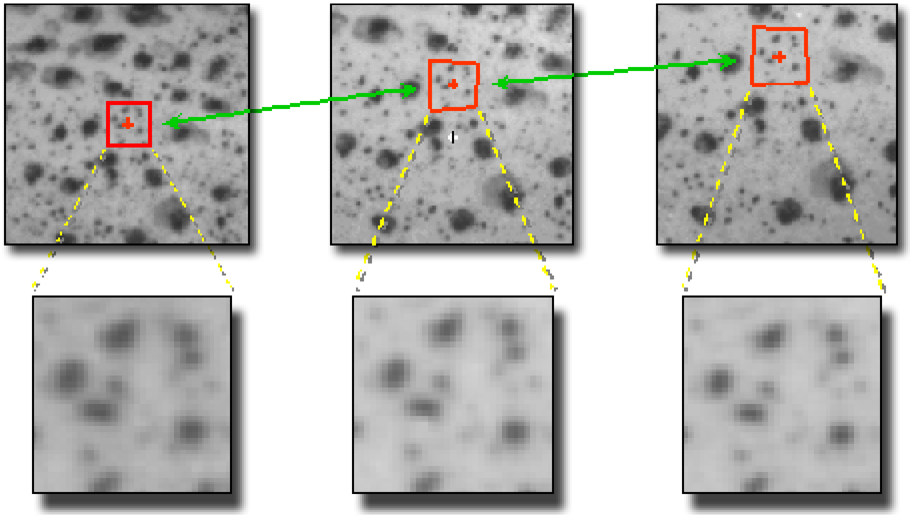
Variable Strain to failure



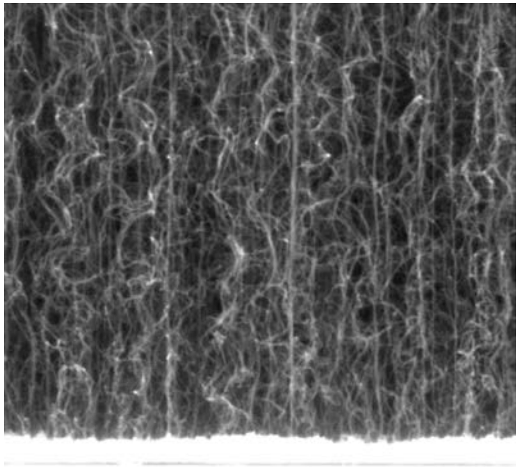
Column Aspect Ratio (ht/width)

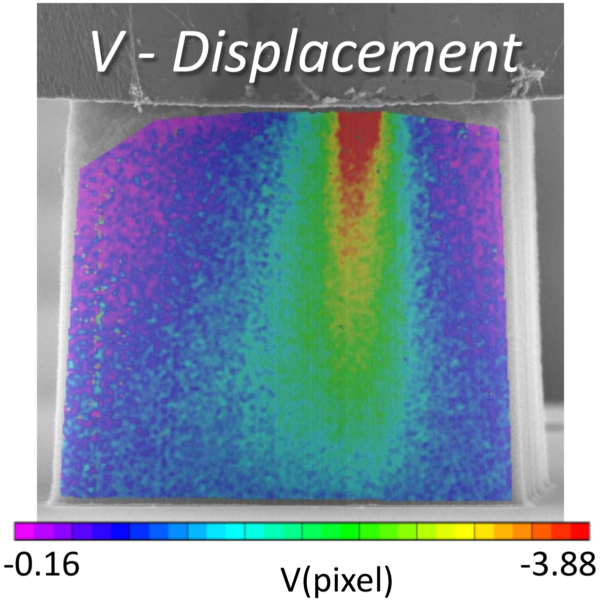
M. Maschmann, G. Ehlert, S.J. Park, D. Mollenhauer, B. Marauyama, A.J. Hart, J. Baur, *in review.*

3. New Method for in-situ CNT Array Mechanics: Digital Image Correlation



Courtesy of Correlation Solutions, Inc.
http://www.correlatedsolutions.com



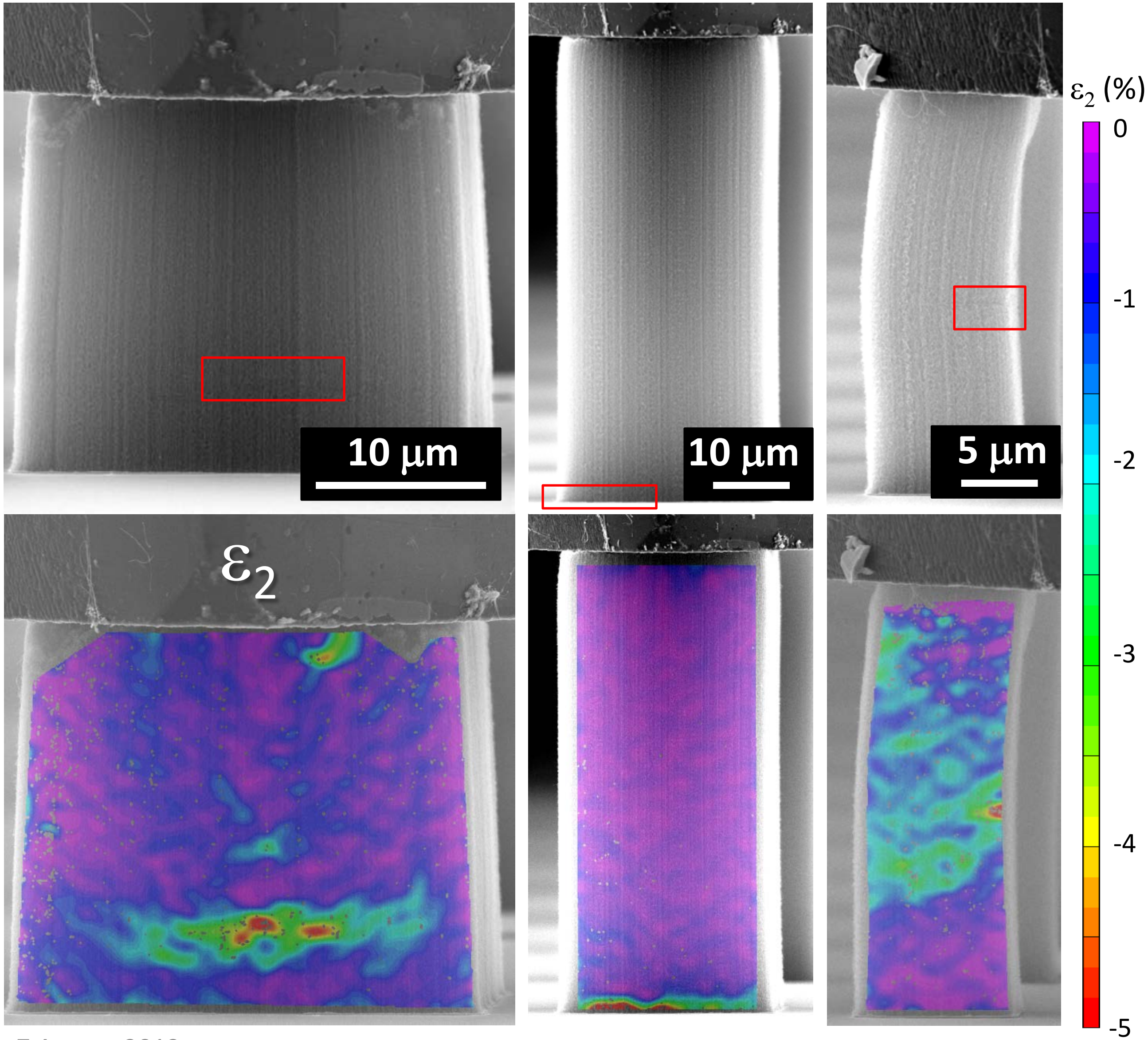


Tracking motion of CNTs enables computation of full-field displacement and strain maps

M. Maschmann, G. Ehlert, S.J. Park, D. Mollenhauer, B. Maruyama, A.J. Hart, J. Baur, *in review.*

Digital Image Correlation

CNT Array Column Buckling



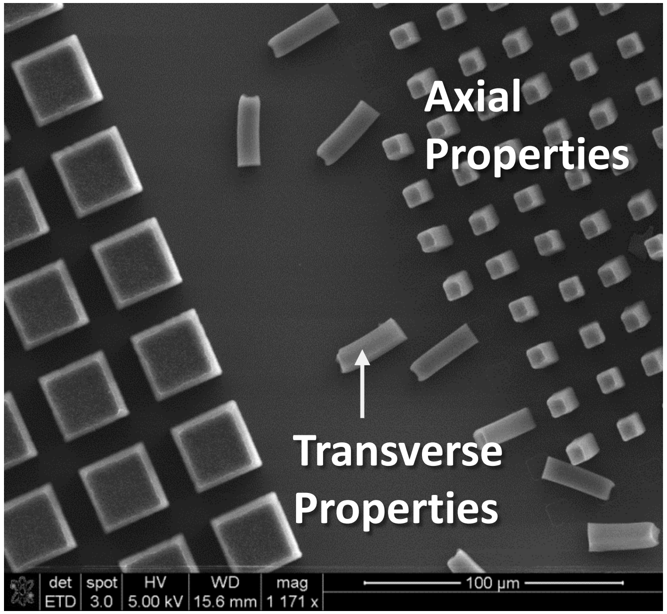
Without DIC:

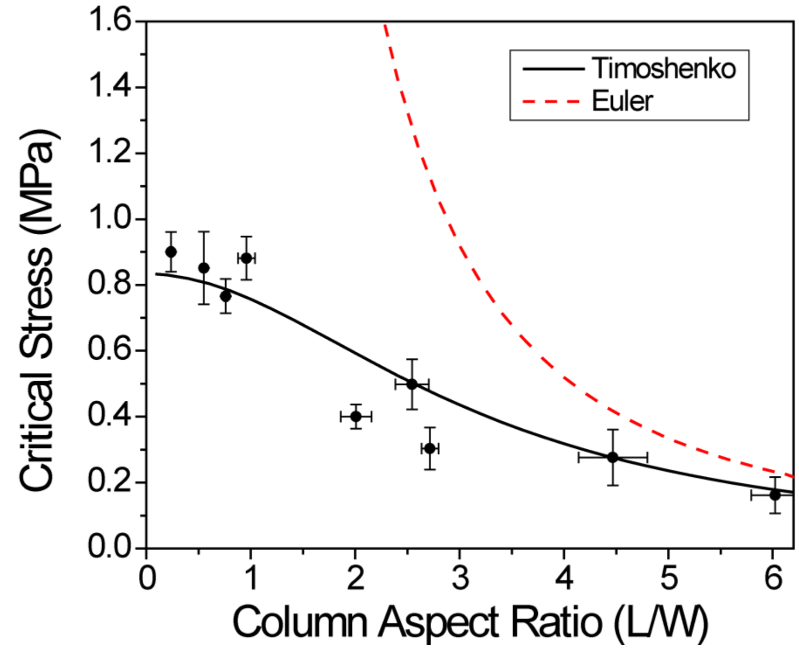
Column buckling is a strong function of column aspect ratio

With DIC:

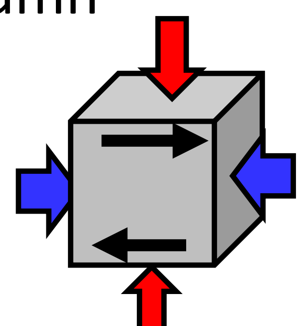
CNT array yielding is independent of column aspect ratio and initiates at 5% (ε_2)

Continuum-like CNT Properties





- DIC reveals *inelastic* column buckling
- Significant anisotropy reduces column strength
- Inelastic Timoshenko beam theory predicts critical stress of CNT array columns



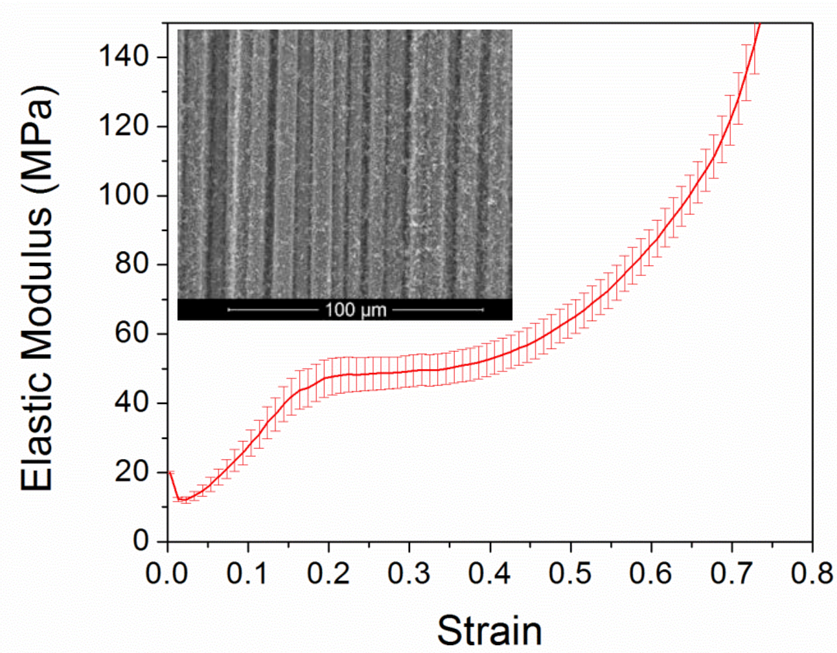
E_{Axial} = 400 - 700 MPa

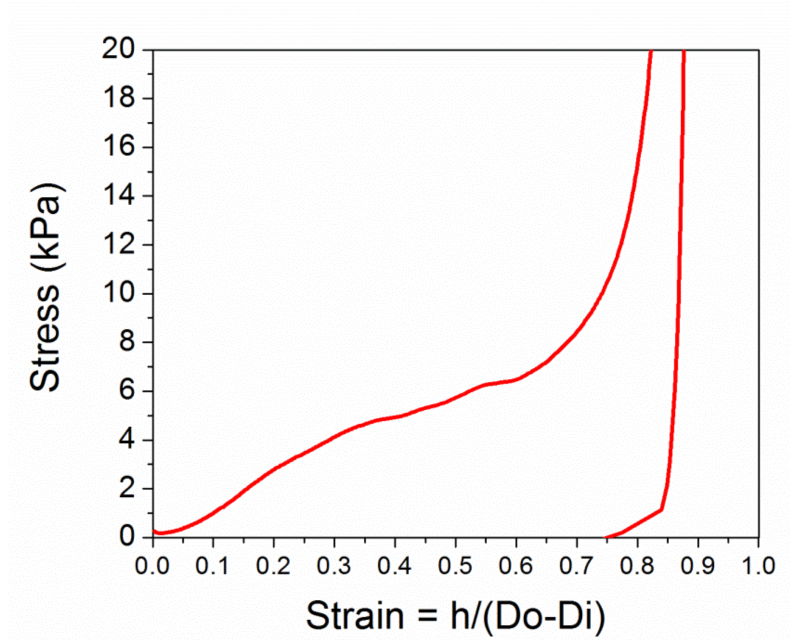
E_{trans} = 2.5 - 4.0 MPa

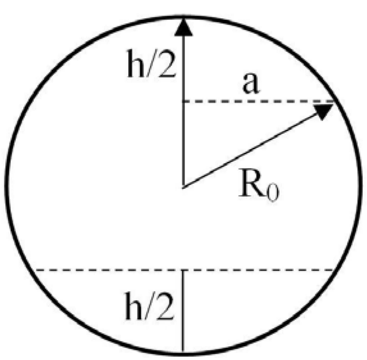
G_{trans} = 0.8 - 1.6 MPa

Strain <5% (elastic regime)

Compression of CNT Fuzzy Fibers





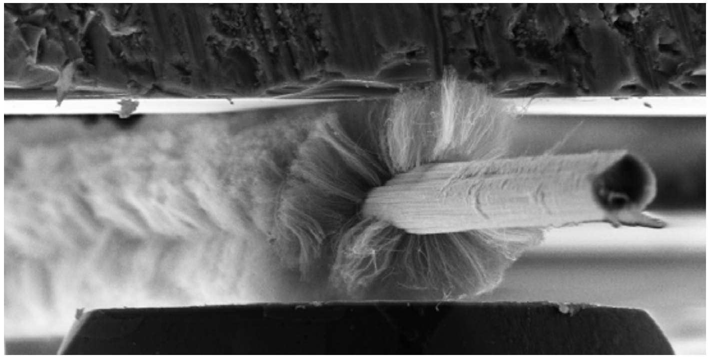


$$a = \sqrt{R_0 h - h^2/4}$$

Contact Area = 100µm * 2a(h)

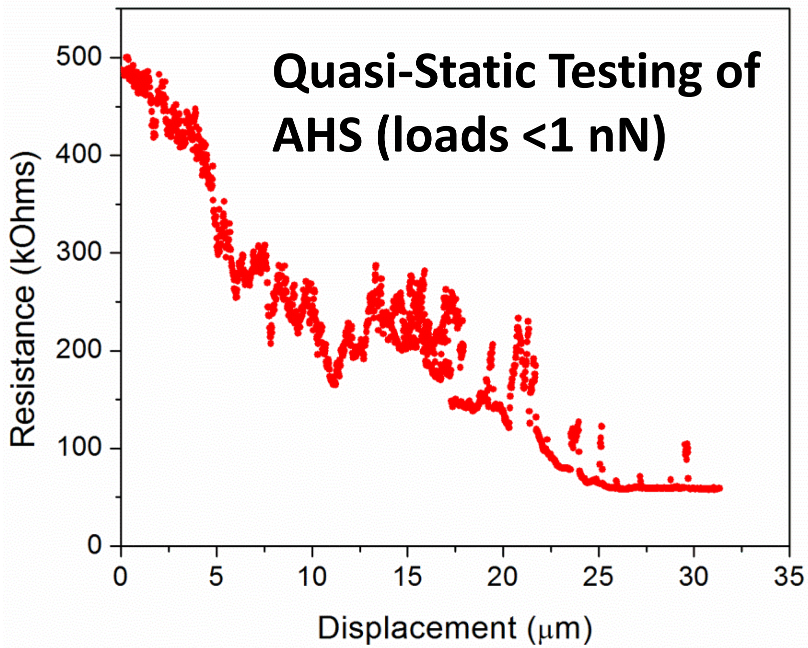
$$E = \frac{\text{Contact Stiffness} * (D_0\text{-}D_{CF})}{\text{Contact Area}}$$

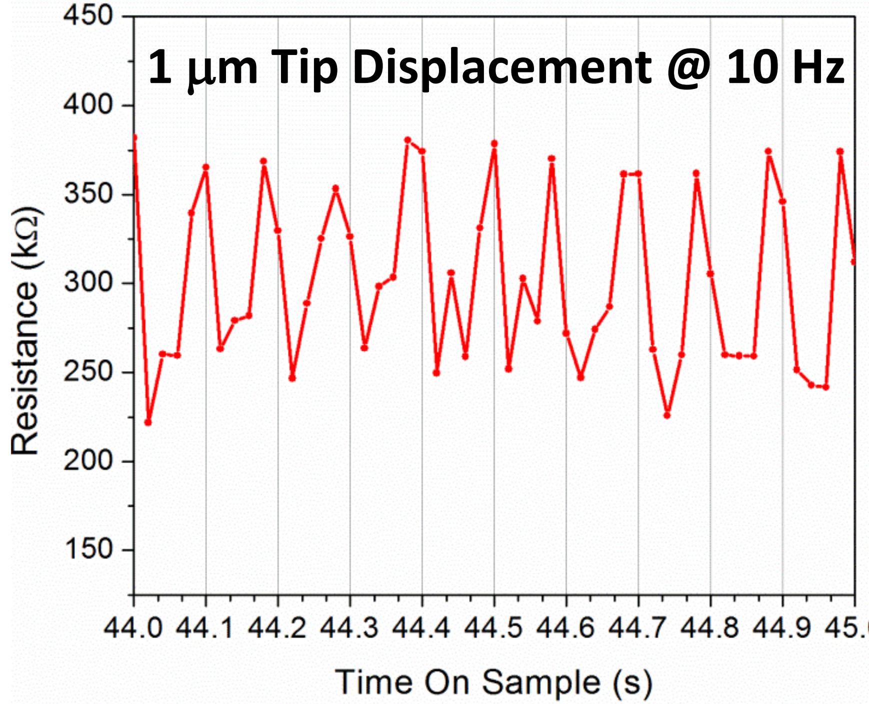
h = indent depth
D_0 = CNT + CF Outer Diameter
D_{CF} = CF Outer Diameter

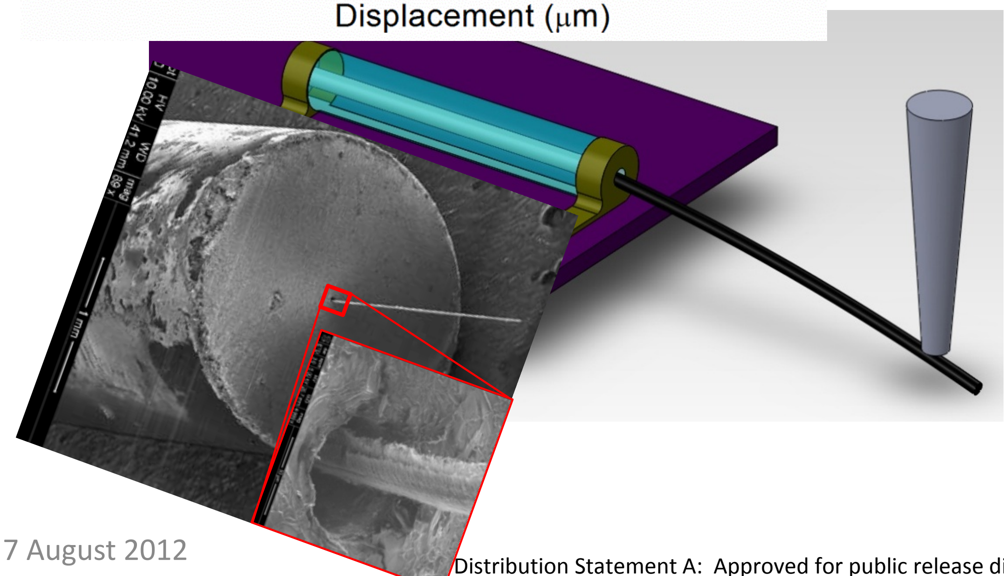


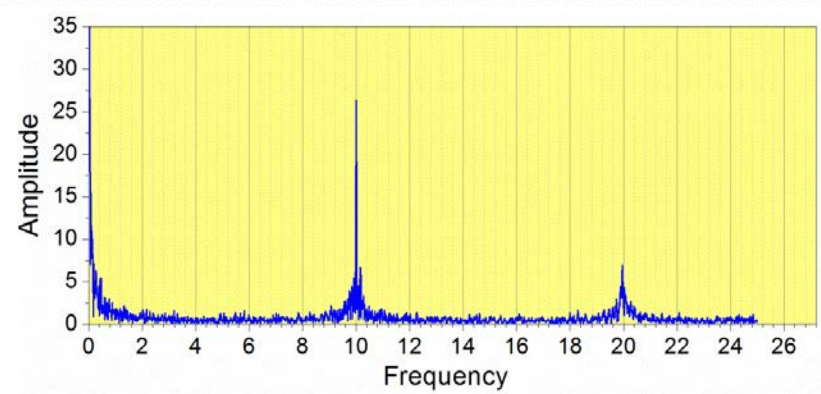
4. Artificial Hair Sensor

Prototype Performance





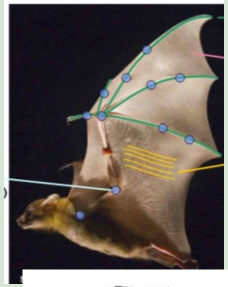




Embedded Sensors for Air Vehicles

LRIR 09RW10COR – **Dickinson (RW)** / Baur (RX) / Reich (RQ)

Bio-like Flow Sensing



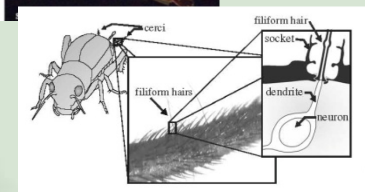
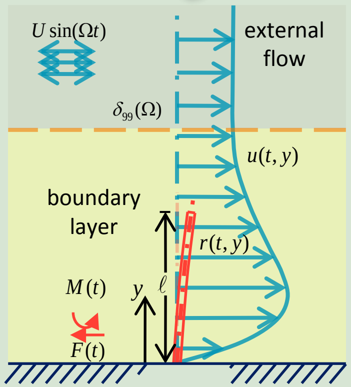


Figure 1. Filiform hairs on the cerci of crickets[1].

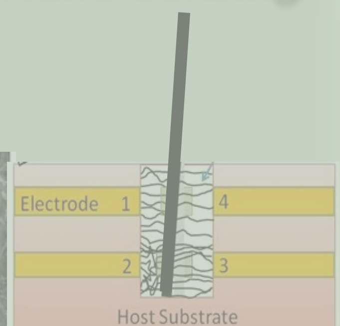


Ben Dickinson - RW

1. **Response of carbon fiber hair in oscillating flow?**
2. **Why didn't we observe any vibration in the carbon fiber?**
3. **Frequency response of carbon fiber hair?**
4. **Forces involved in the dynamic response of the carbon hair?**

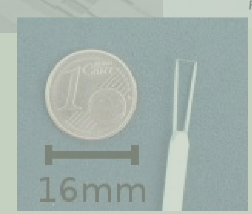
?

Hierarchical Fiber Nano-sensing

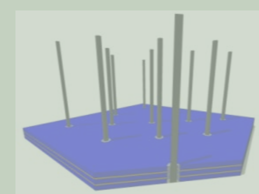


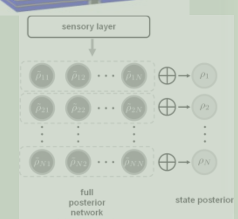
Jeff Baur - RX

"Insect Grade" Sensors to "Feel"



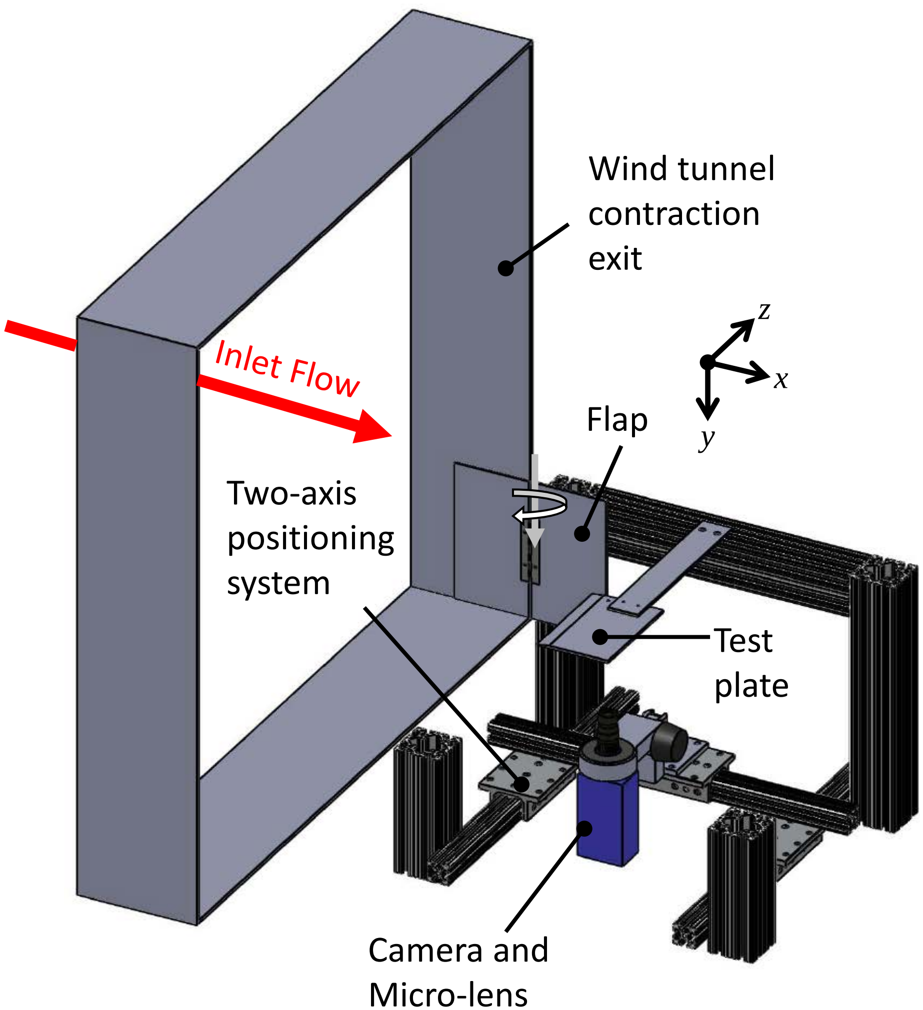
VS.

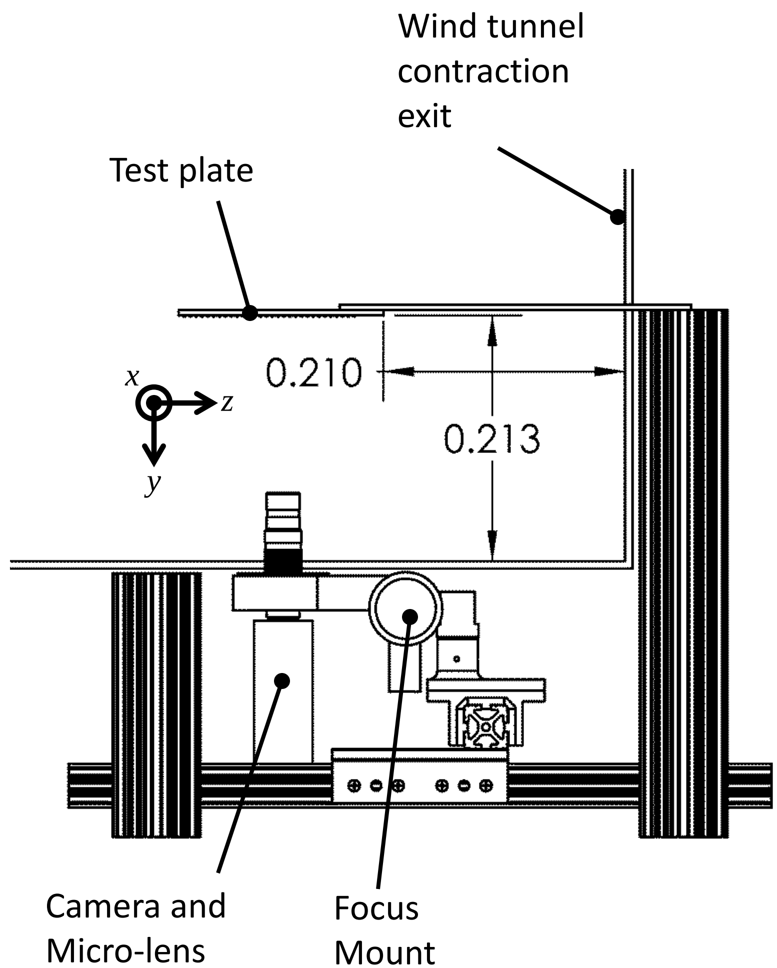




Greg Reich - RQ

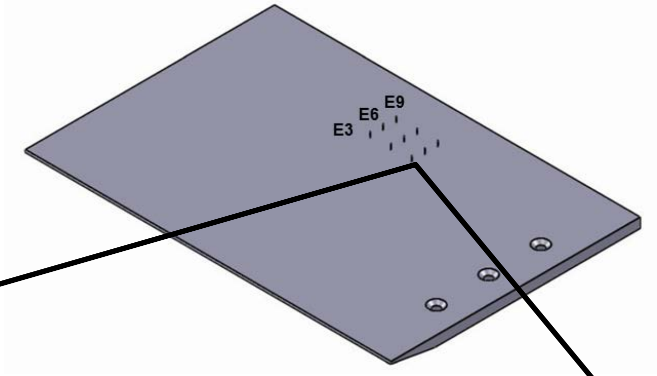
Wind tunnel setting, hair array fixed to flat plate

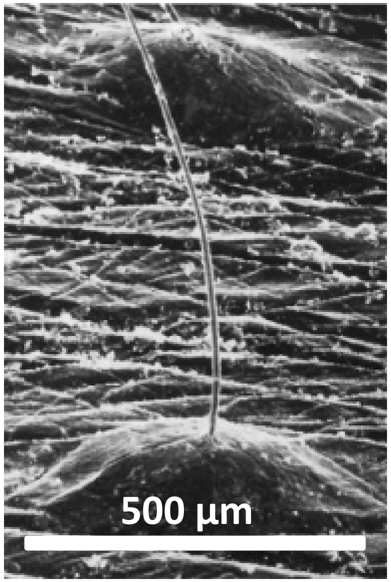




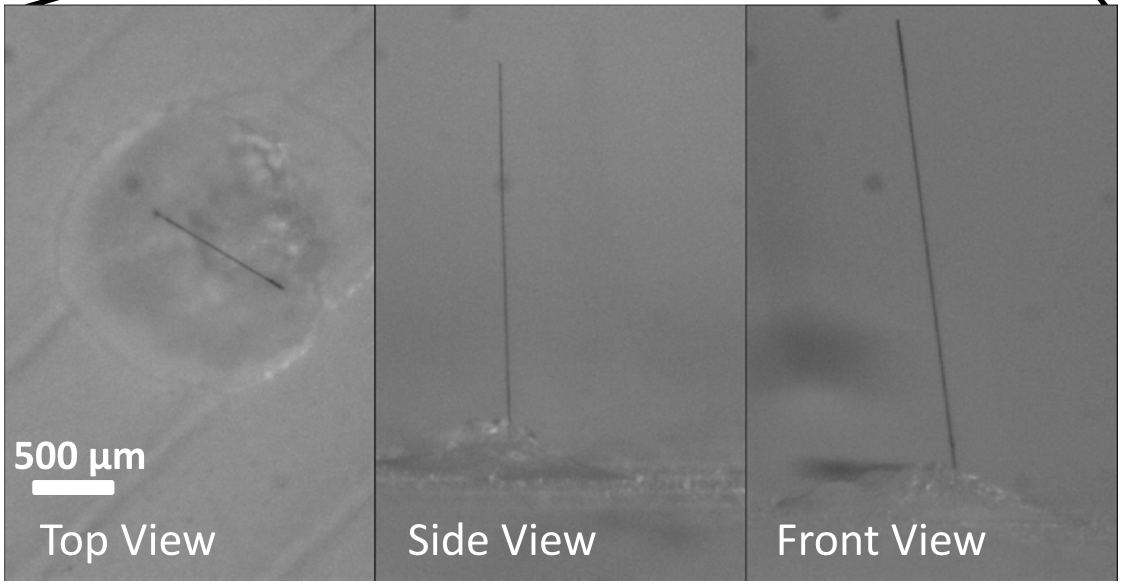
Hair array fixed to flat plate

Thornel T-650 pan based carbon fiber	
Density	1.77e3 kg/m^3
Aspect ratio	300:1
Elasticity	2.55e11 Pa



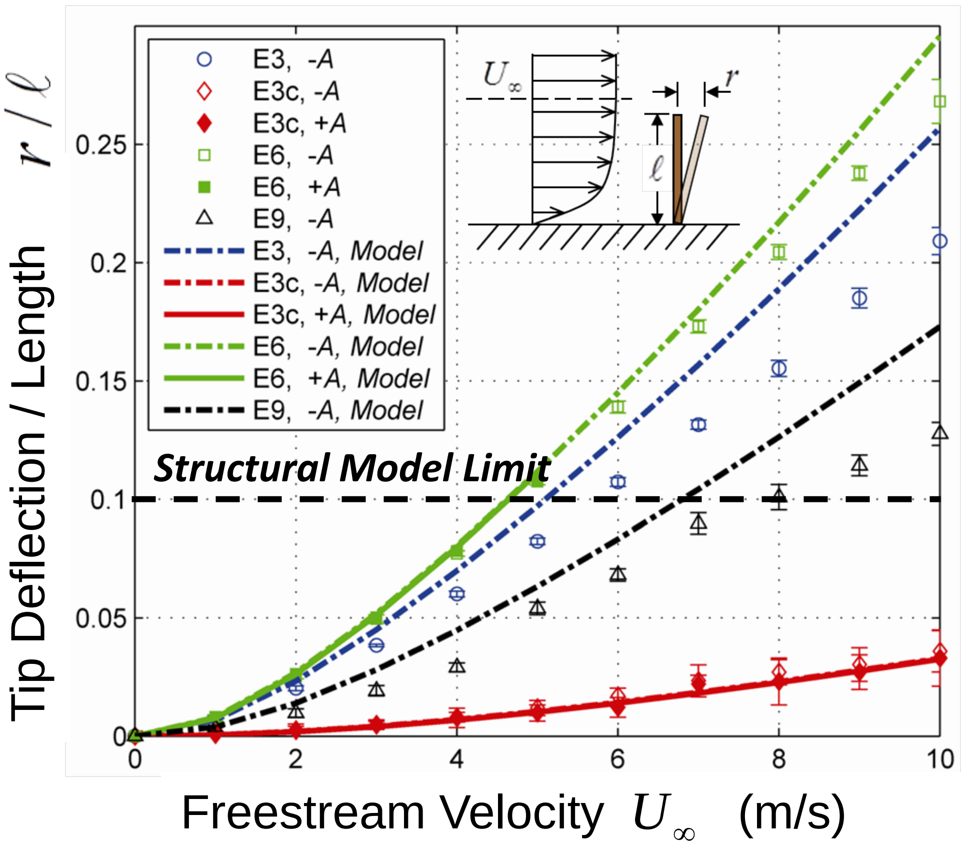


Bat wing hair receptor from Hall, Aust J Zool, v 1994



McClain, Case, and Dickinson, submitted to AIAA Journal, 2012 .

Displacement predictions in steady laminar boundary layer vs experiment

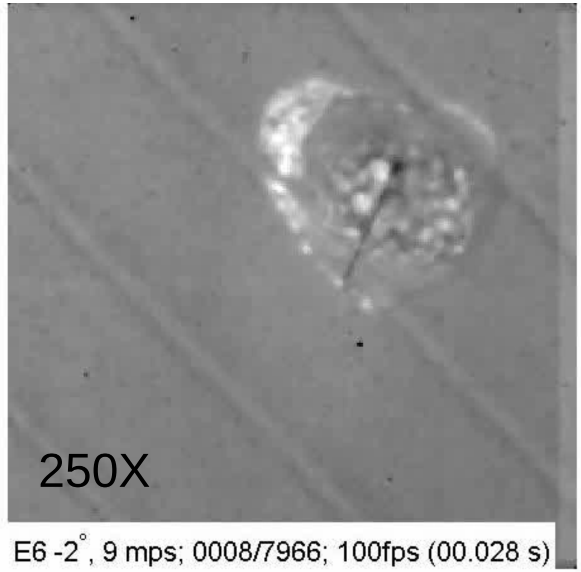


- $Re_{hair} = 4$
- $Re_x = 50,000$

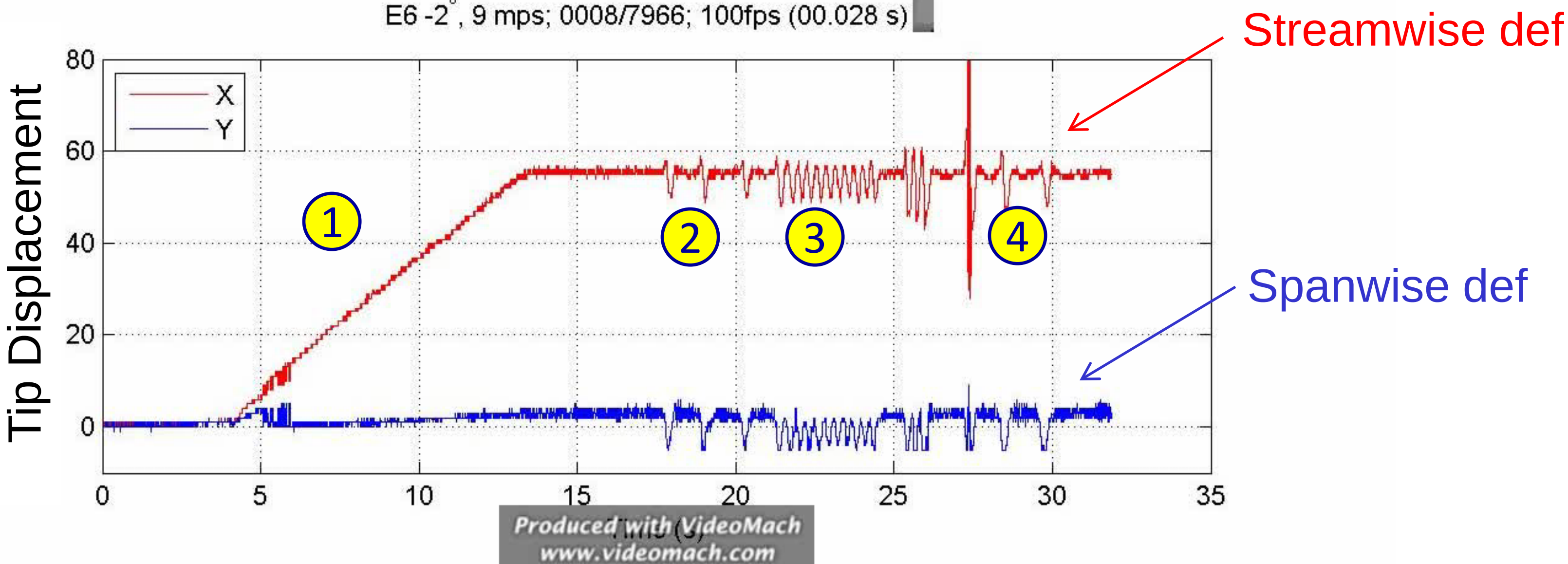
McClain, Case, and Dickinson, submitted to AIAA Journal, 2012 .

Preliminary observations of carbon hair-structure dynamic response

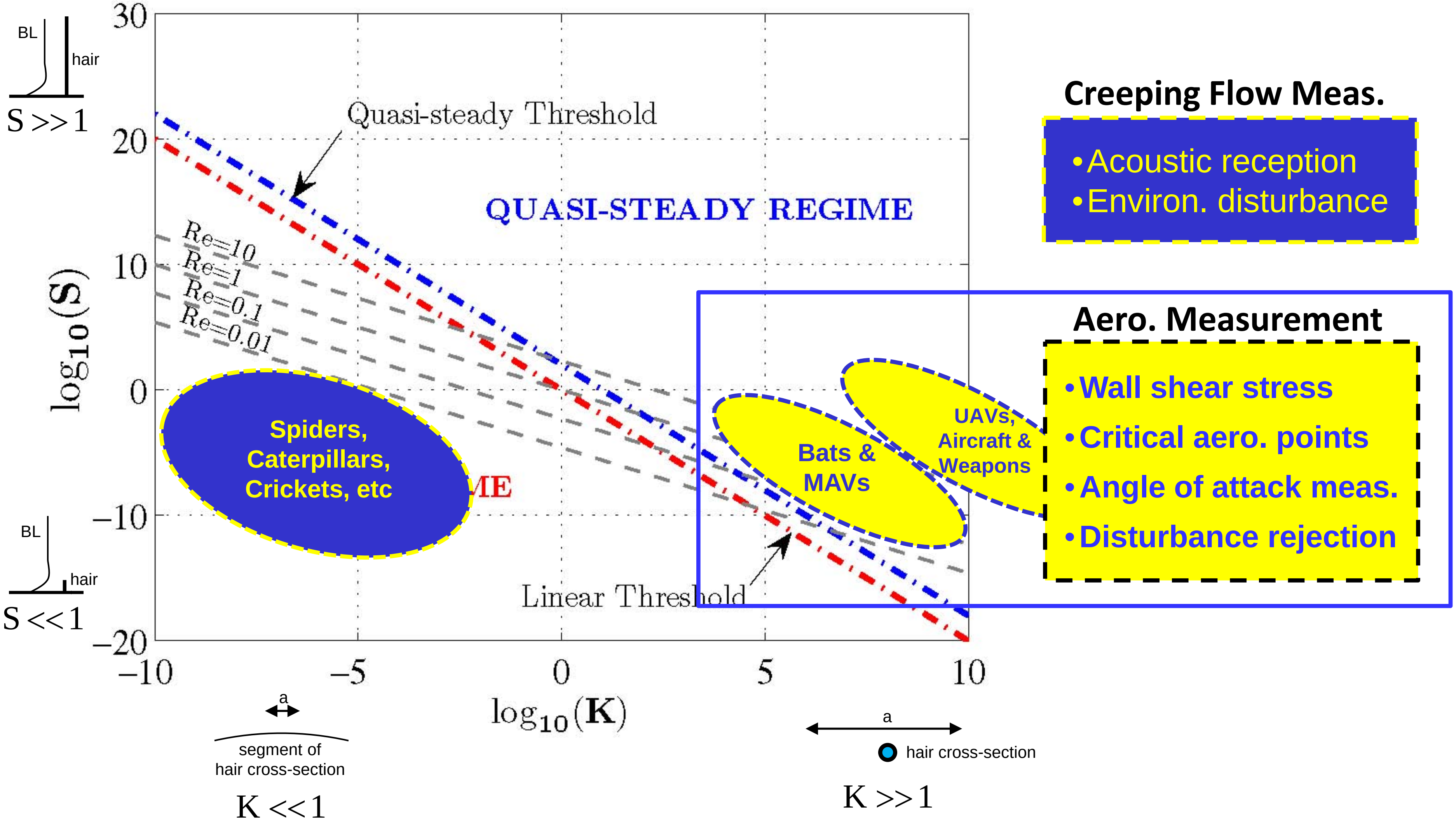
1. flow ramp to 9 m/s
2. 3 discrete gusts
3. Oscillatory gusts
4. 1 large gust with two small gusts



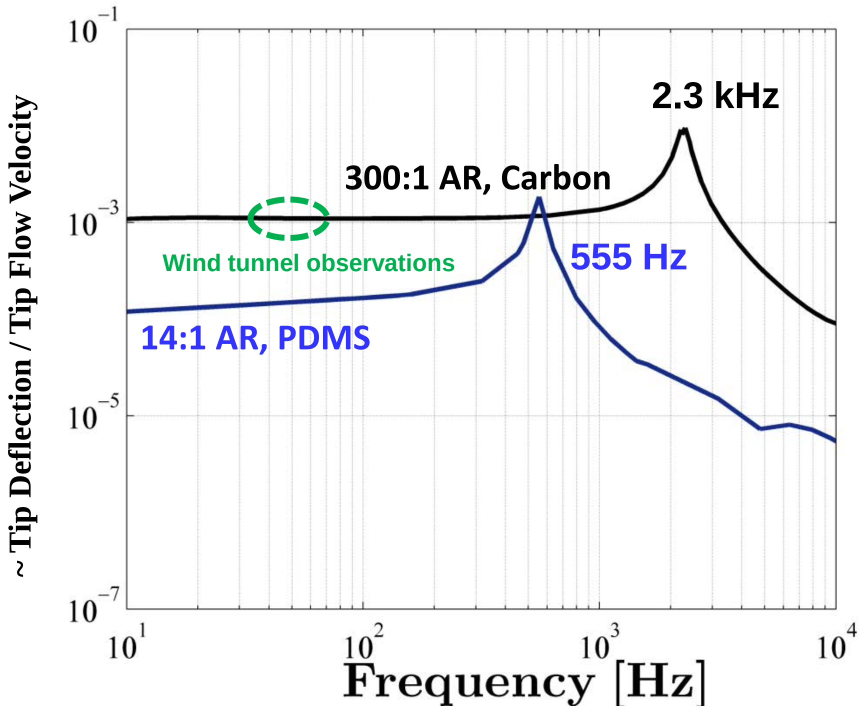
Streamwise Flow Dir

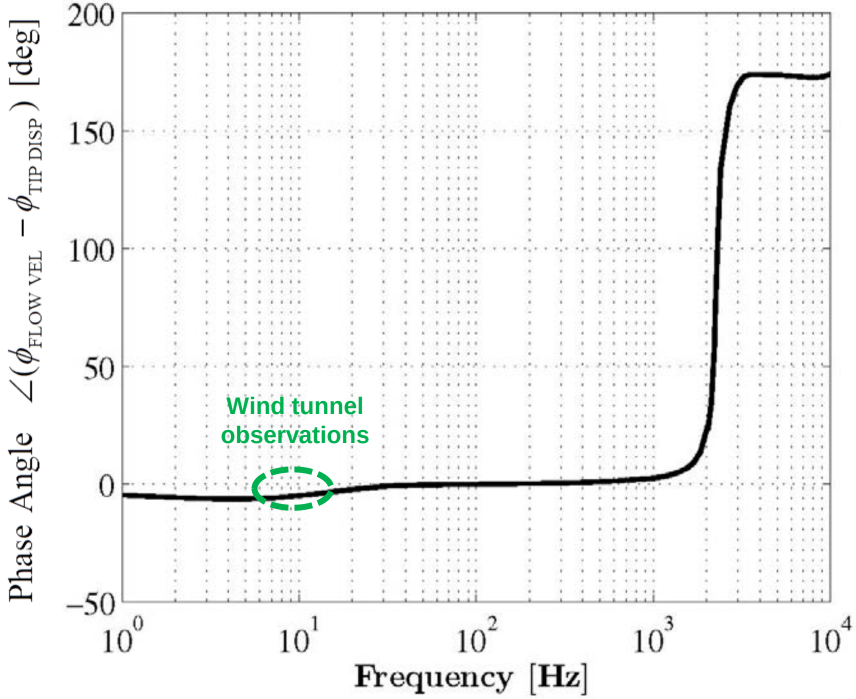


The Dynamic World of Hair-Structures



Frequency response of carbon hair in oscillatory boundary layer





Hair structure response like 2nd order system

$$C(s)=\frac{Y(s)}{U(s)}=\frac{1}{(s/\omega_n)^2+2\zeta(s/\omega_n)+1}$$

Embedded Sensors for Air Vehicles

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Bio-like Flow Sensing

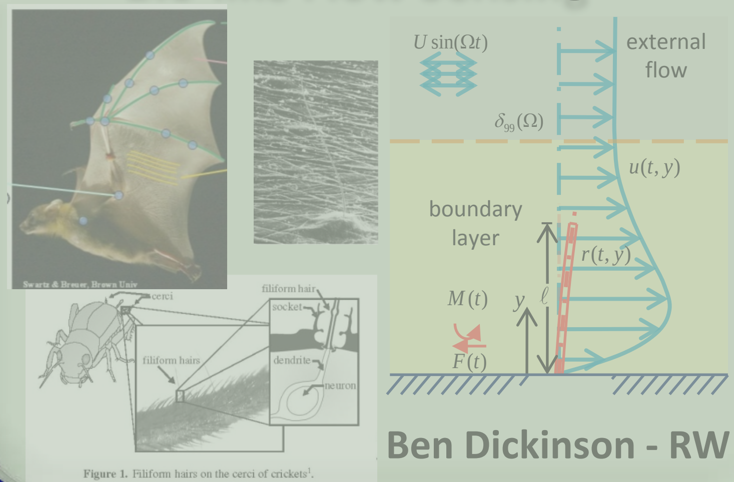
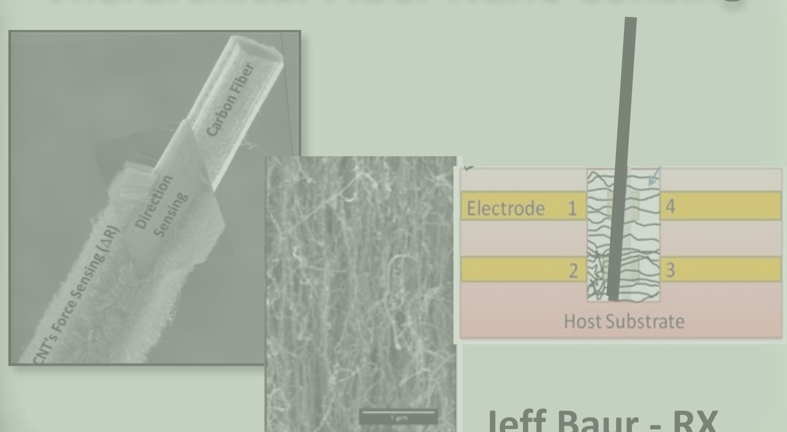


Figure 1. Filiform hairs on the cerci of crickets[1].

Ben Dickinson - RW

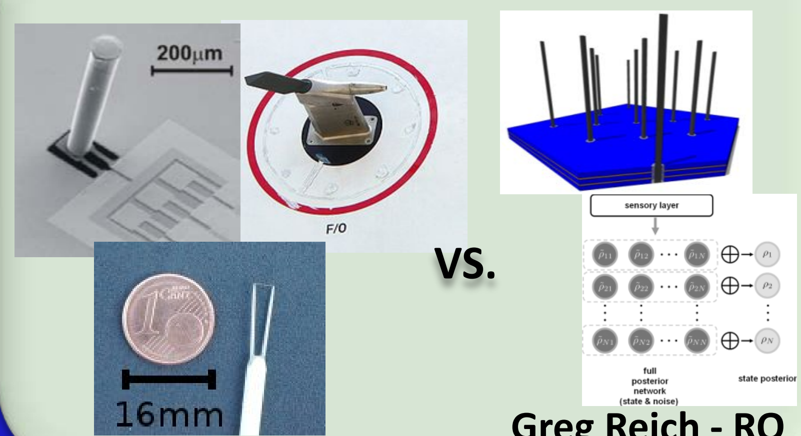
1. Limits of using arrays of "Insect Grade" noisy sensors ?
2. Methods for AHS arrays to provide flow state information for flight control or "feel"
3. AHS advanced estimation algorithms and approaches ?

Hierarchical Fiber Nano-sensing



Jeff Baur - RX

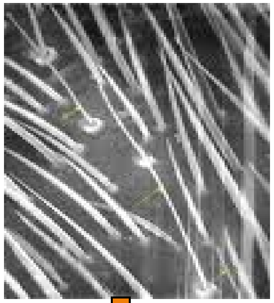
"Insect Grade" Sensors to "Feel"

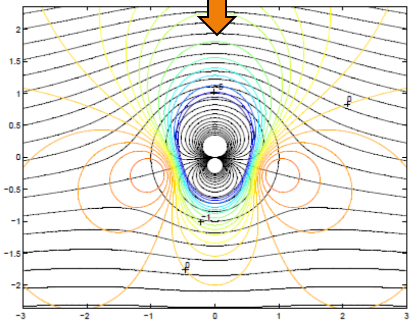


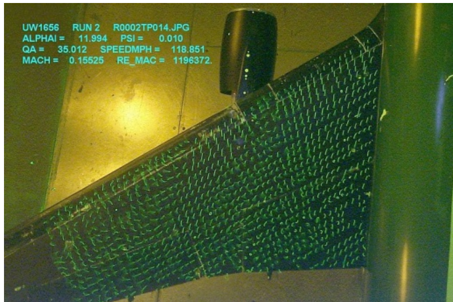
Greg Reich - RQ

Future Work: AHS Control Investigation

- **Flow state estimation**
  - Distributed arrays of sensors as an integrated solution rather than point sensors
  - Signal processing to collect information from array
  - Reduced-order modeling for estimation of potential flow
- **Flow and structure fusion**
  - Unmodeled dynamics, unsteadiness, etc
  - Time scales of AHS better than other sensors
  - Kalman Filter/Bayesian Estimation
- **Putting it together and demonstration with flight control**
  - Simulations, HIL, scaled flights

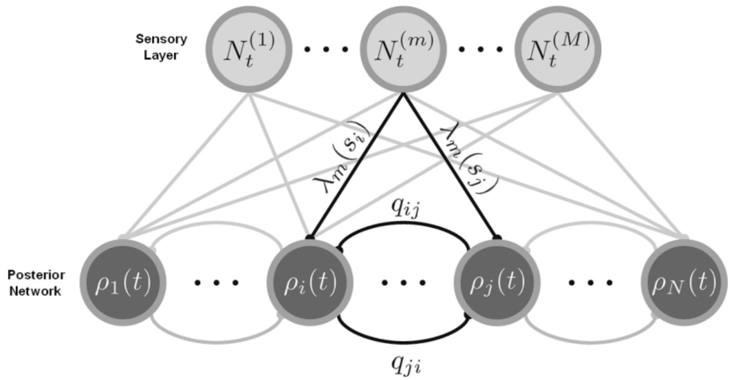


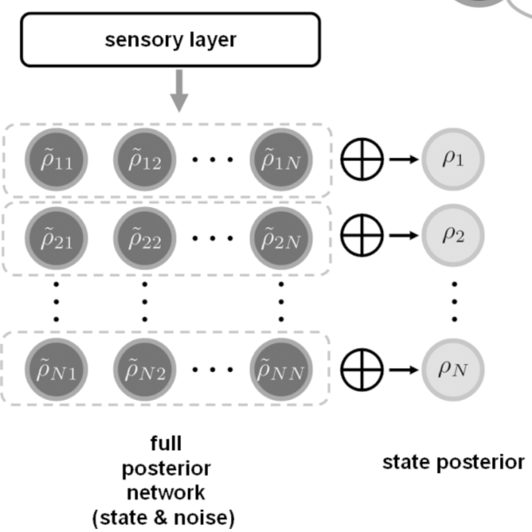




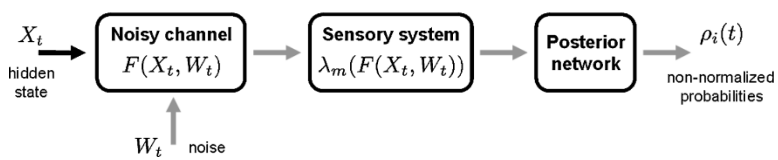
Insect-Grade (Noisy) Sensors

1. Bayesian Filtering (neuroscience)

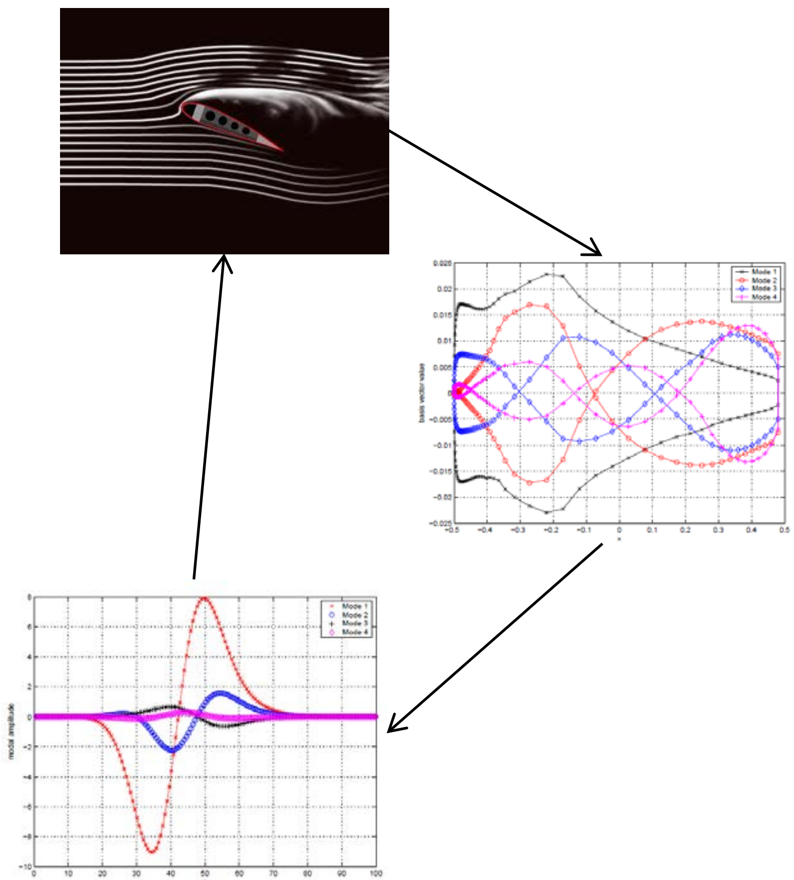




Bobrowski, Meir, Eldar, "Bayesian Filtering in Spiking Neural Networks: Noise, Adaptation, and Multisensory Integration," *Neural Computation*, **21,** 1277-1320 (2009)



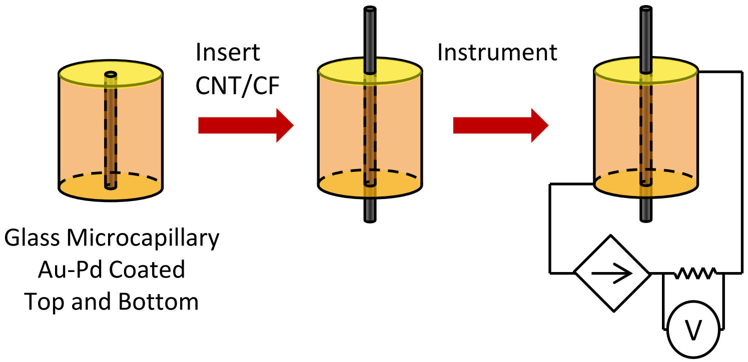
2. Process Decomposition (POD)



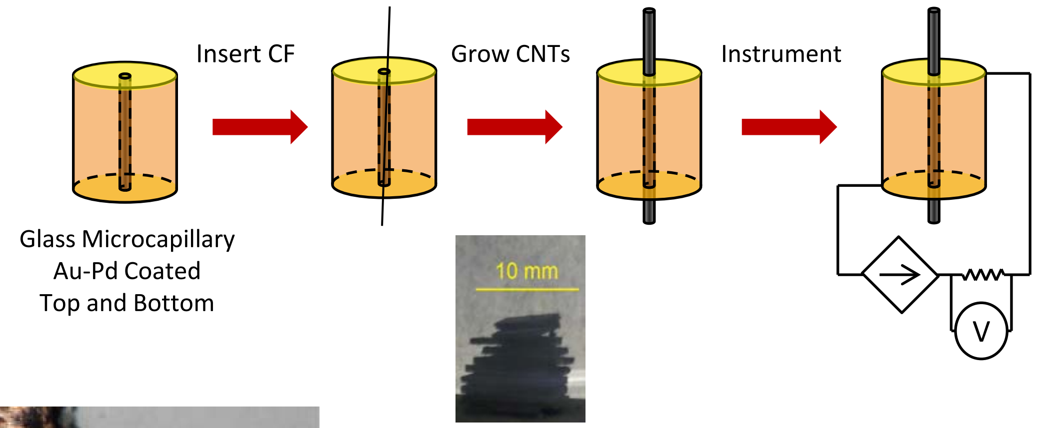
Willcox, "Unsteady Flow Sensing and Estimation via the Gappy Proper Orthogonal Decomposition," *Computers and Fluids*, **35/2,** 208-226 (2006)

Next Steps - Prototype Design

Ex situ CNT Growth



In situ CNT Growth



Si Wafer Stack Expanded by *in situ* CNT Growth

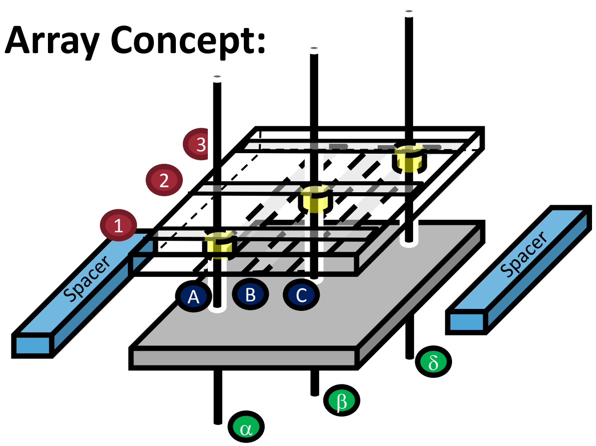
Step One: Structural Integration of a Single Sensor Pore

- Identify potential substrate materials for sensor integration as appliqué or surface-bonded treatment
- Address single CNT “hair plug” integration with electrical ingress/egress
- Demonstrate sensor viability on flexible substrate

Step Two: Array Development

- Identify direct write or alternative printing for application of array electronics on substrate
- Demonstrate interconnect of array leads to sensor pore

Array Concept:



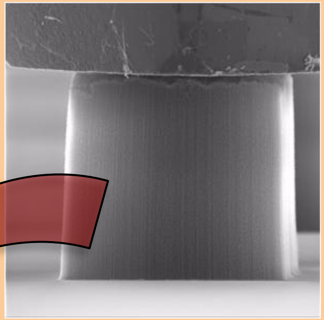
Sensitivities, Requirements, and Disciplines (OH MY!)

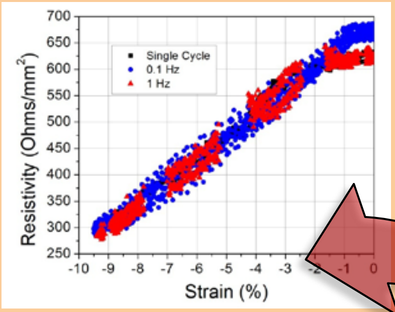
nm

RX

Calculation of sensitivities/ performance

Derivation of requirements

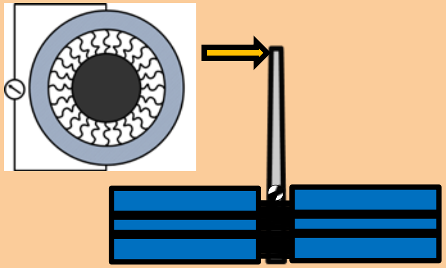


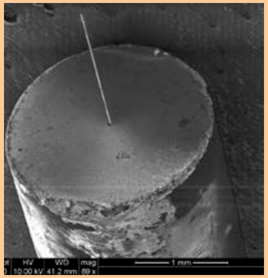


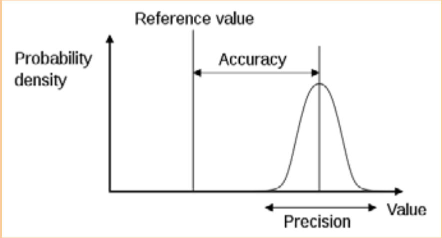
CNT gage factor

mm

RW



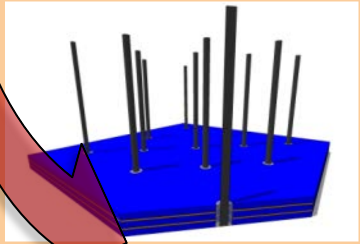


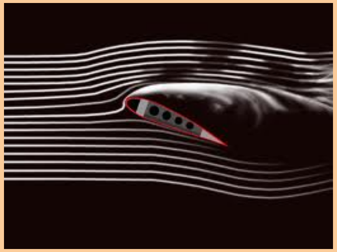


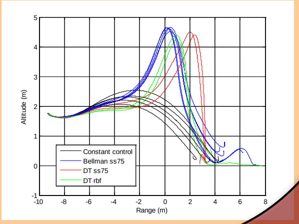
Device accuracy and precision

cm

RQ



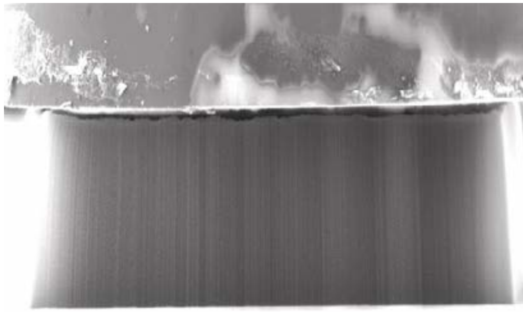




System performance

Summary

- Proof-of-concept of Artificial Hair Sensor with CNT mechano-resistive elements demonstrated
- CNT arrays examined that initially appear mechanically different by length, but DIC reveal a common failure criteria
- Observed carbon hair deflection in-phase with gust-like disturbances without vibration - mapped the flow regime steady/ unsteady
- Computed frequency response plots for carbon hair structure in quasi-steady regime – 2nd order like response
- Found that elasticity and drag dominated the force balance in the carbon hair structure
- Established criteria based on dimensionless groups to control hair dynamic response through selection of material and geometric properties



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